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Yield-Based Management Zones and Grid Sampling Strategies: Describing Soil Test and Nutrient Variability

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ABSTRACT

Alternatives such as yield-based management zones may solve problems associated with grid soil sampling while effectively describing soil test and nutrient variability. The main objective was to delineate yield-based management zones using multiyear yield data and compare them with whole-field average and grid soil-sampling methods to determine the most effective strategy for describing soil test and nutrient variability. Research was conducted in four continuous no-till fields that had varied cropping histories and yield monitor data for at least 3 yr from 1996 through 2000. Four yield-based management zone methods, (i) mean normalized yield map (MNY), (ii) coefficient of variation map (CVM), (iii) MNY × CVM, and (iv) yield region map (YRM), were evaluated. Three grid soil-sampling strategies, (i) grid cell, (ii) grid center, and (iii) grid center with kriging at two sampling distances (68 and 98 m), were also tested. Grid cell sampling consistently captured more soil test and nutrient variability than the grid center and grid center with kriging methods. Of the yield-based management zone strategies, YRM was the most effective and in all four fields explained more soil test and nutrient variability compared with the whole-field average approach. Yield region map also performed better than or similar to the 98-m grid center and 98-m grid center with kriging strategies. When the field had low soil test values, YRM was also nearly as effective in capturing nutrient recommendation variability as the 98-m grid cell method. However, compared with all other strategies, the 68-m grid cell method was the most effective way to describe soil test and nutrient variability.

The traditional approach to soil fertility management has been to treat fields as homogeneous areas and to calculate fertilizer and lime requirements on a whole-field basis. However, it has been reported for at least 70 yr that fields are not homogeneous, and sampling techniques to describe field variability have been recommended (Linsley and Bauer, 1929). Describing the spatial variability across a field has been difficult until new technologies such as global positioning systems (GPS) and geographic information systems (GIS) were introduced. These technologies allow fields and soil sample locations to be mapped accurately and also allow complex spatial relationships between soil fertility factors to be computed. This in turn has increased interest and use of soil-sampling techniques that attempt to describe the variability in soil fertility factors within a field.

Currently, two grid soil-sampling methods are the most common sampling techniques used to describe the spatial variability of soil fertility parameters. The grid cell method represents an area in which multiple cores are collected and thoroughly mixed together to form a composite sample. The grid center method represents a point, typically the center of a grid cell, in which multiple cores are collected near the point to form a composite sample (Kuhar, 1997; Brouder and Morgan, 2000). A study comparing these two grid sampling methods found that the grid center method paired with an interpolation technique such as kriging or inverse distance weighting explained more soil test P and K variability than the grid cell method (Wollenhaupt et al., 1994).

Besides determining which grid sampling method to use, there are other problems a grower must resolve before grid soil sampling can be implemented on-farm. The first problem is how to determine the proper grid size to use in a given field. A study by Wollenhaupt et al. (1994) in Wisconsin found that grid sampling on a 98-m grid described up to 69% of soil test P and up to 97% of soil test K variability in two fields. They further reported that by decreasing the grid size, larger percentages of the variability in soil test P and K could be captured. Franzen and Peck (1995) showed that to correctly capture the spatial variability in pH, P, and K of an Illinois field, soil samples needed to be taken on a 68-m grid. These studies demonstrate that no single grid size is applicable for all fields and that as the variability in soil fertility parameters increases, grid size should decrease. Compounding the difficulty in determining the proper grid size for sampling a field, studies by Cahn et al. (1994) and Cambardella and Karlen (1999) reported that the correct grid size or sampling distance varied not only by field, but also by soil fertility parameter. Consequently, the optimal grid size at which to sample a field is usually unknown before sampling.

The second problem growers must face is the profitability of grid sampling. Grid soil sampling typically requires a large number of samples and may cost $2.50 per hectare or more over a 4-yr sampling cycle (Swinton and Lowenberg-DeBoer, 1998). An economic study on the profitability of grid soil sampling for soil test P and K across multiple sites and crops found that the profitability varied depending on crop. Grid sampling in low-value crops such as wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) was not profitable while grid sampling in higher-value and/or higher-yielding crops such as corn (*Zea mays* L.) was profitable in many instances (Swinton and Lowenberg-DeBoer, 1998).

Researchers have suggested that management zones

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Abbreviations: CV, coefficient of variation; CVM, coefficient of variation map; GIS, geographic information system; GPS, global positioning system; MNY, mean normalized yield map; NCDA&CS, North Carolina Department of Agriculture and Consumer Services; YRM, yield region map.

of uniform production potential may offer a solution to the problems associated with grid soil sampling while still effectively describing soil fertility variability. Soil map units (Wibawa et al., 1993), topography (Kravchenko et al., 2000), remote sensing (McCann et al., 1996), electrical conductivity sensors (Sudduth et al., 1997; Lund et al., 1999; Johnson et al., 2003), and producer experience (Fleming et al., 2000) have all been used with varying success to delineate management zones. However, creating management zones from yield maps offers advantages over these alternative methodologies. First, many growers in the USA have routinely collected yield maps. In fact, USDA's Agricultural Resource Management Survey (USDA Econ. Res. Serv., 2004) reported that from 1996 through 2002, 16 to 37% of corn, 13 to 29% of soybean (*Glycine max* L.), and 6 to 9% of wheat acres in the USA were mapped using a yield monitor. Yield maps are also the only source of data that provides direct information on how the performance of management factors such as soil fertility impacts yield. Therefore, yield maps may offer growers a method that utilizes existing data to improve nutrient management within their fields. Early research on the use of yield maps found that classification of multiyear yield data could be related to soils data (Lark and Stafford, 1997). Subsequent research by Lark and Stafford (1998), Blackmore (2000), and Diker et al. (2002) has suggested that the use of multiyear yield maps to delineate management zones for soil sampling is promising. Nevertheless, these studies lacked an in-depth analysis regarding the accuracy of yield-derived management zones for describing soil test and nutrient variability.

The main objective of this research was to determine if multiyear yield data could be used to delineate management zones that would accurately describe soil test and nutrient variability. Specifically, we wanted to compare the effectiveness of the yield-based management zones for capturing soil test and nutrient recommendation variability with: (i) whole-field average management, (ii) grid cell sampling, (iii) grid center sampling, (iv) grid center sampling with kriging, and (v) a series of control regions based on random spatial division.

MATERIALS AND METHODS

Experimental Sites

This research was conducted on four continuous no-till fields in the Piedmont region of North Carolina. The fields ranged in size from 22.6 to 36.4 ha and are characterized by clay loam surficial soil textures (Table 1). Each field had a varied cropping history that included corn, winter wheat, and soybean. Yield data were collected for each crop between 1996 and 2000 using a yield monitor (AgLeader 2000, AgLeader Technol. Inc., Ames, IA) with differential GPS. Nutrient management for each field was based on the North Carolina nutrient recommendations (Tucker et al., 1997) for P, K, and lime on a whole-field basis.

Soil Sampling

Soil samples were collected in 1998 (Fields 3 and 4) and in 2002 (Fields 1 and 2). Soil samples in Fields 3 and 4 were taken on a 68-m rectangular grid. In Fields 1 and 2, soil samples were taken on a 34.8-m equilateral triangular grid to achieve greater sampling efficiency. Soil samples were obtained following the soil sampling recommendations of the Agronomic Division of the North Carolina Department of Agriculture and Consumer Services (NCDA&CS) for no-till fields. At all sampling points, seven soil cores were taken to a depth of 10 cm from within a 1.5-m radius around the sample point and combined to form a composite sample. The NCDA&CS analyzed the composite samples for P, K (Mehlich-3), pH (water), and lime requirement (Mehlich–buffer acidity). These analyses were calculated based on volume, and thus all soil test values are reported using units of volume. Nutrient recommendations for P, K, and lime were calculated for each soil-sampling point using the standard North Carolina nutrient recommendations (Tucker et al., 1997) for corn, soybean, and wheat, which are equivalent.

Whole-Field Average Management

For each field, the whole-field average management treatment was calculated as the mean soil test P, K, and pH values

Table 1. Soil type, taxonomic name, field size, yield-mapped crops, mean yield, and yield standard deviation (SD) of each crop for each of the four study fields.

Field	Soil type	Taxonomic name	Field size	Yield-mapped crops	Mean yield	Yield SD
			ha		kg ha^{-1}	
1	Mecklenburg clay loam	fine, mixed, thermic Ultic Hapludalfs	36.4	1997 full-season soybean	2825	652
				1999 winter wheat	5280	639
				1999 double-cropped soybean	1977	693
				2000 full-season soybean	2798	639
2	Cecil clay loam	clayey, kaolinitic, thermic Typic Kanhapudults	25.9	1996 corn	5179	2944
				1997 winter wheat	4284	1312
				1997 double-cropped soybean	1742	841
				1999 winter wheat	4937	1022
				1999 double-cropped soybean	2421	592
				2000 full-season soybean	2610	612
3	Hiwassee clay loam	fine, kaolinitic, thermic Typic Rhodudults	26.9	1998 winter wheat	3551	679
				1998 double-cropped soybean	1749	572
				1999 full-season soybean	3565	552
				2000 winter wheat	5630	874
4	Hiwassee clay loam	fine, kaolinitic, thermic Typic Rhodudults	22.6	1996 corn	4890	2712
				1997 winter wheat	3767	1507
				1997 double-cropped soybean	2072	915

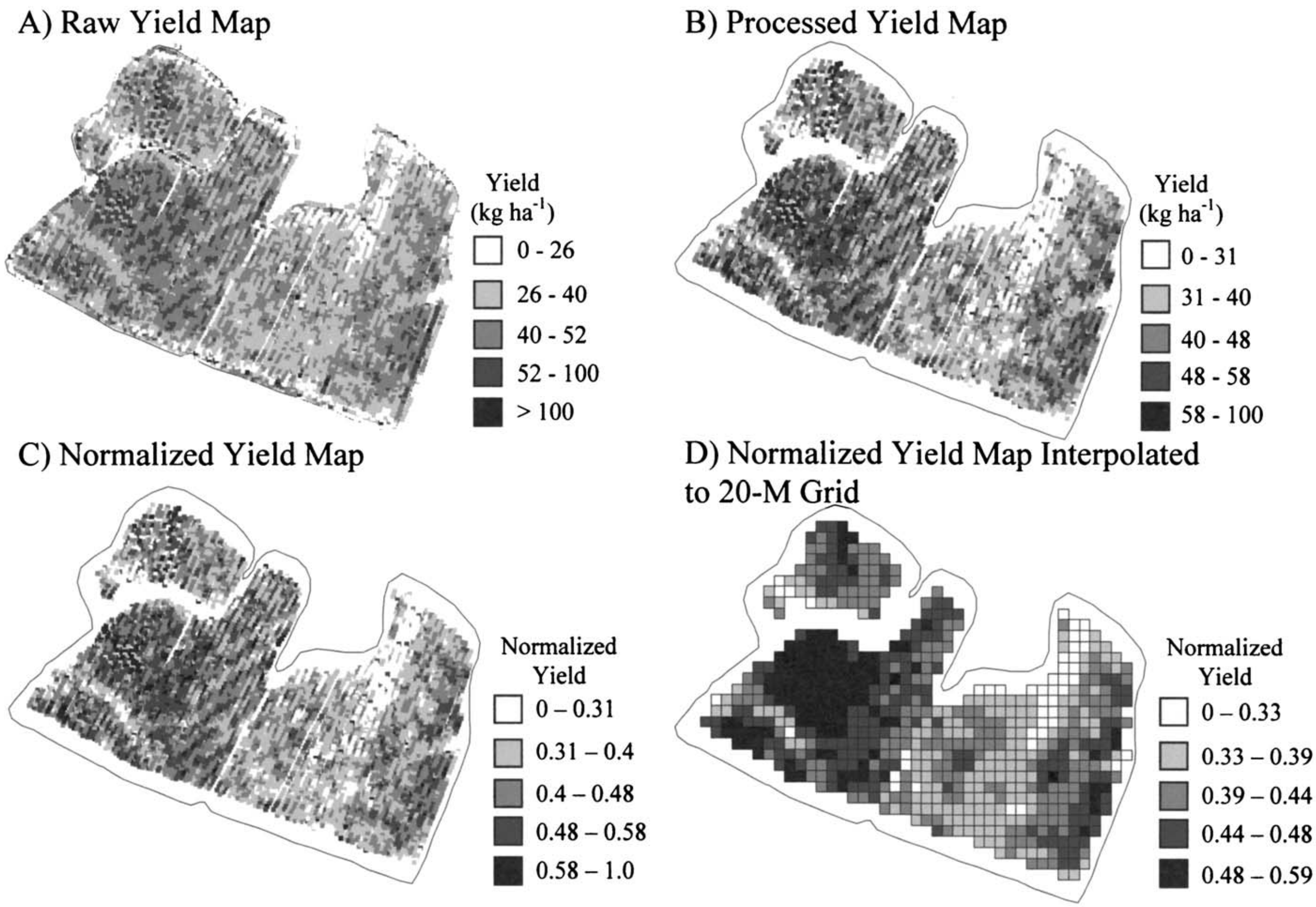

Fig. 1. Processing of yield data beginning with (A) the raw yield map and proceeding through (B) processing, (C) normalization, and (D) interpolation to a 20-m grid for Field 1.

of all the soil samples within a field. The mean P, K, and lime recommendation values were also calculated using all of the soil samples within a field. This approach was not intended to represent current soil-sampling practices and whole-field management but was used to determine the best nonbiased estimate of the whole-field average of soil test P, K, and pH as well as the P, K, and lime recommendation values.

Yield-Based Management Zones

Before management zones could be delineated, the raw yield maps (Fig. 1A) were processed (Fig. 1B) to remove common errors associated with harvesting and yield-monitoring equipment and handling. We used the general guidelines of Blackmore and Moore (1999) and Weisz et al. (2003), which were

1. yield data associated with field edges and narrow passes were removed,
2. a further 6 s (≈16 m) of yield data on all field edges were removed to ensure that sufficient grain flow occurred through the harvester and yield-monitoring system to provide accurate readings, and
3. any remaining outliers were removed from the data set.

After processing, each yield map was normalized by dividing by the maximum yield in the map (Fig. 1C). The normalized yield maps from a given field were then interpolated to common 20- by 20-m rasters with local variograms and block kriging using VESPER (Fig. 1D; Minasny et al., 1999).

From these normalized yield maps, four types of yield-based management zones were developed. The first, a MNY, was constructed using the mean value for each 20- by 20-m raster across all seasons and crops (Fig. 2A). The MNY was then divided into three classes (high, medium, and low) delineated using the Jenks optimization procedure (Fig. 2C; Jenks, 1967). This procedure minimizes the within-class variance and maximizes the between-class variance. The second type of management zone was a CVM, calculated as the coefficient of variation (CV) for each 20- by 20-m raster across all seasons and crops (Fig. 2B). The CVM was divided into two classes (stable or low CV and unstable or high CV) delineated using the Jenks optimization procedure (Fig. 2D; Jenks, 1967). The third type of management zone was calculated by combining the MNY and CVM maps (MNY × CVM), resulting in six classes (high/stable, high/unstable, medium/stable, medium/unstable, low/stable, and low/unstable; Fig. 3A).

In the three types of yield-based management zones described above (MNY, CVM, and MNY × CVM), a "management zone" was defined as the group of rasters within a map with the same classification. Consequently, it was possible to have individual 20- by 20-m rasters having the same classification (i.e., they were in the same "management zone") while being spatially noncontiguous. This could result in the smallest spatial management unit being as little as 20 by 20 m (see Fig. 2). One of the objectives of forming management zones is to define management "regions," which can potentially be soil sampled as homogenous areas within a field. A 20- by 20-m "region" is impractical for this purpose. Therefore, the

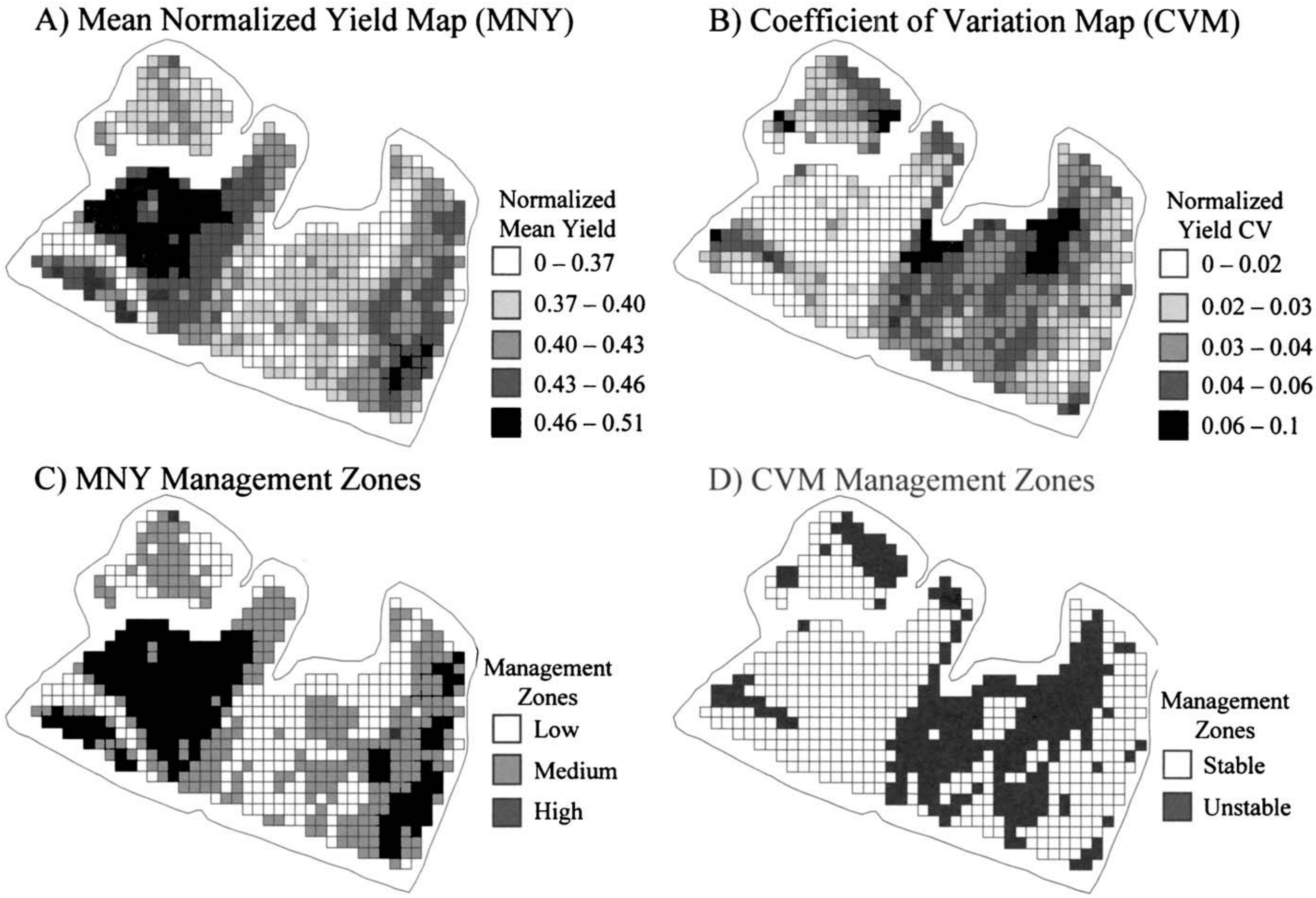

Fig. 2. The creation of (A) the mean normalized yield map (MNY), (B) the coefficient of variation map (CVM), and (C and D) the subsequent classification into management zones for Field 1.

fourth type of yield-based management zone we developed was based on converting the MNY × CVM classification map into a YRM (Fig. 3B). To do this, the MNY × CVM map was divided into distinct spatial regions using the following rules:

1. A yield-based region must be at least 0.4 ha in size.
2. Rasters with high MNY are always separated from those with low MNY; when necessary, the medium MNY rasters may be used as a transition.
3. As possible, rasters of the same MNY class (or like mixtures of MNY classes) are kept together.

For each yield-based management zone map (MNY, CVM, MNY × CVM, and YRM), the mean soil test P, K, and pH values as well as the mean P, K, and lime recommendation values were calculated by zone. Mean zone calculations were determined using all the soil samples contained within a delineated management zone.

Grid Sampling Methods

Three grid sampling methods (grid cell, grid center, and grid center with kriging) were evaluated at two sampling distances (68 and 98 m) in Fields 1 and 2 and one sampling distance (98 m) in Fields 3 and 4. Rectangular grids were used for these evaluations. For the grid cell method, a mean soil test P, K, and pH value and a mean P, K, and lime recommendation value were calculated for each grid cell using all the soil samples contained within the grid. The grid center method differs from the grid cell method by using the soil test P, K, and pH value and the P, K, and lime recommendation value for the soil sample point nearest the center of the grid. The grid center with kriging method used the grid center soil test P, K, and pH and P, K, and lime recommendation values to interpolate (conventional kriging with a whole-field variogram for each variable using VESPER; Minasny et al., 1999) values at each sample location across the field.

Grid sampling methods are generally based on a computer-generated grid that is draped across a map of the field. Usually, the user subjectively sets the alignment and starting point for the grid. It is possible that the degree of soil variability captured by any specific grid sampling method is, at least in part, due to this subjective placement and alignment. To ensure that the grid sampling methods we were evaluating were not biased due to this subjective spatial position within the field, three replications of each rectangular grid, with the grids themselves changing spatial and angular position, were created and evaluated.

Control Regions

As fields are divided into smaller management units (whether yield-based management zones or regularly spaced sampling grids), the degree of soil variability captured will generally increase. Thus, if a yield-based management zone technique describes more soil variability than whole-field management, this could simply be the result of managing on a smaller scale. To test this possibility, we compared the performance of all the yield-based management zones and grid sampling methods with randomly generated spatial subdivisions (control regions) of each field. These control regions were constructed by randomly dividing each field into a number of equal-sized areas equivalent to the number of grid sampling cells or yield-based management zones using a script within ArcView GIS (ESRI, ESRI Inc., Redlands, CA) produced by William Huber at Quantitative Decisions (Quantitative Decisions, Merion Station, PA). For each control region, the mean soil test P, K, and pH values as well as mean P, K, and lime recommendation values were calculated using all the soil samples contained within the control region. Additionally, to ensure that the control regions were not biased due to spatial position within the field, the division of the field into control regions was performed three times, each with a different spatial arrangement of the control regions, and each of these replications was evaluated.

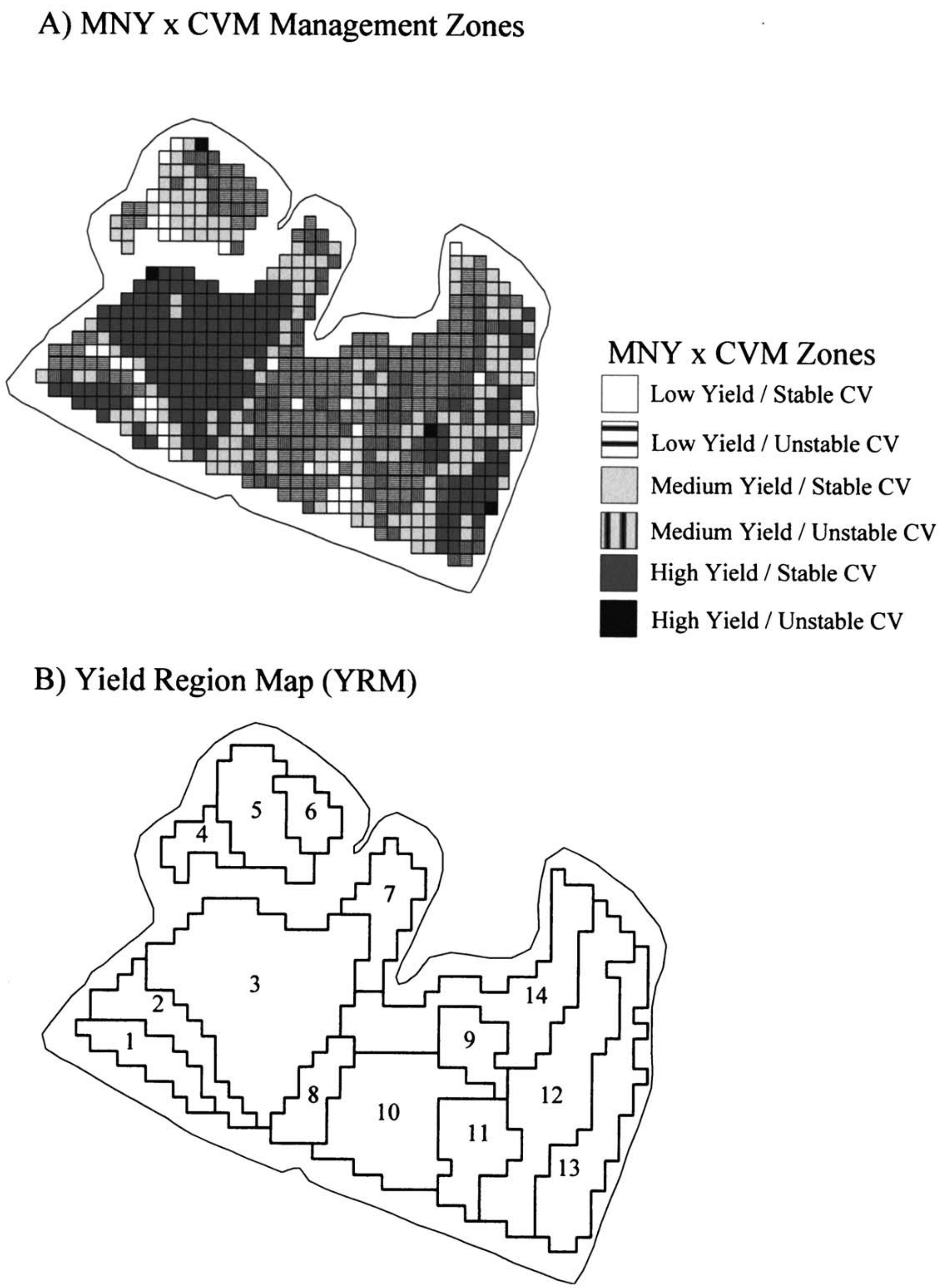

Fig. 3. The combination of the Field 1 mean normalized yield map (MNY) and coefficient of variation map (CVM) into (A) the MNY $\times$ CVM map with six management zones and the subsequent division into (B) a yield region map (YRM) with 14 management zones based on the delineation rules.

Data Analysis

Evaluation of each sampling strategy was based on an estimation of the soil test P, K, and pH residual variance and a P, K, and lime recommendation residual variance associated with each method (i.e., the variation in these parameters that the management/sampling method was unable to account for). These variance estimations are described below.

Whole-Field Average, Yield-Based Management Zones, Grid Cell, and Control Region Methods

Evaluation of these sampling strategies was based on a weighted soil test P, K, and pH variance and a weighted P, K, and lime recommendation variance for each management zone, control region, or grid as described by Fridgen et al. (2000) such that:

$$S_z^2 = \frac{1}{n_z}\sum_{i=1}^{n_z}(Y_i - \overline{Y}_z)^2 \times \frac{n_z}{n_t} \quad [1]$$

where S_z^2 = the weighted variance for zone, region, or grid z; Y_i = soil test P, K, or pH value or P, K, or lime recommendation value for soil sample point i; $\overline{Y}_z$ = mean soil test P, K, or pH or mean P, K, or lime recommendation for zone, region, or grid z; n_z = number of soil sample points in zone, region, or grid z; and n_t = total number of soil sample points in the field.

Once the weighted variance for each zone, region, or grid was computed, the total residual variance associated with the sampling method was computed such that:

$$S_t^2 = S_1^2 + S_2^2 + S_3^2 + ... + S_z^2 \quad [2]$$

where S_t^2 = total residual variance and S_z^2 = the weighted variance for zone, region, or grid z.

Grid Center Method

To calculate a weighted soil test P, K, and pH variance and a weighted P, K, and lime recommendation variance for each grid in the grid center method, Eq. [1] must be modified such that:

$\overline{Y}_z = Y_{cen}$ = the soil test P, K, or pH value or the P, K, or lime recommendation value for the sample point closest to the center of grid z.

Calculation of the total residual variance is then computed the same as in Eq. [2].

Grid Center with Kriging Method

To calculate the total residual variance within a field associated with the grid center with kriging method, Eq. [1] must be modified to allow each soil sample point to be compared with the kriged valued for that soil sample point such that:

$S_z^2 = S_t^2$ = total residual variance;

$\overline{Y}_z = Y_{ik}$ = the kriged soil test P, K, or pH value or P, K, or lime recommendation value for soil sample point i.

The interpretation of the total residual variance was facilitated by comparing them with the whole-field average method values. It was assumed that the whole-field average method would generally have the highest total residual variance. Consequently, the values for this method were all set to 100%. The total residual variance for each of the other sampling strategies was expressed as a percentage of that found for the whole-field average method. There are no statistical tests that can be used to determine if the difference between residual variance found for two treatments is statistically different. Consequently, we established that when a treatment's residual variance differed by 15 or more percentage points from the corresponding control region, we assumed that treatment differed from a random field division.

RESULTS AND DISCUSSION

Whole-Field Management

Values of the whole-field total residual variance for soil test P ranged from 215 g^2 m^{-6} in Field 1 to 573 g^2 m^{-6} in Field 2 (Tables 2–5). Similarly, the whole-field

Table 2. The total residual variance calculated from Eq. [2] for soil test P, K, and soil pH as well as P, K, and lime nutrient recommendations for Field 1 by sampling strategy. All values are rounded to three significant figures.

		Total residual variance					
		Soil test values			Nutrient recommendations		
Sampling strategy	Number of zones, grids, or regions	P	K	pH	P	K	Lime
		g^2 m^{-6}			kg^2 ha^{-2}		$(kg^2$ $ha^{-2}) \times 10^4$
Whole-field average	1	215	5980	0.063	1060	952	115
CVM†	2	210	5980	0.058	1040	950	125
Control regions‡	2	199	5180	0.059	1010	841	127
MNY§	3	207	5960	0.053	1020	950	101
Control regions‡	3	204	4710	0.058	1040	749	112
MNY × CVM¶	6	204	5840	0.053	1000	950	105
Control regions‡	6	193	4760	0.059	980	755	110
YRM#	14	187	3570	0.045	931	699	83.4
Control regions‡	14	168	3190	0.049	854	567	103
98-m grid cell‡	42	136	2220	0.038	688	414	79.2
98-m grid center‡	42	263	3890	0.074	1358	643	123
98-m grid center w/kriging‡	42	190	2730	0.053	970	482	117
Control regions‡	42	141	2430	0.037	711.9	449	76.5
68-m grid center‡	82	195	3130	0.056	965	478	163
68-m grid cell‡	82	102	1600	0.029	518	306	57.2
68-m grid center w/kriging‡	82	181	4200	0.052	927	498	114
Control regions‡	82	108	1730	0.024	552	345	70.2

† Yield-based coefficient of variation map (CVM) management zone method.
‡ Indicates that the values reported are the mean of three replications for each grid sample or control region method.
§ Yield-based mean normalized yield (MNY) management zone method.
¶ Yield-based combination of the MNY and CVM management zone methods.
# Yield-based yield region map (YRM) management zone method.

Table 3. The total residual variance calculated from Eq. [2] for soil test P, K, and soil pH as well as P, K, and lime nutrient recommendations for Field 2 by sampling strategy. All values are rounded to three significant figures.

Sampling strategy	Number of zones, grids, or regions	Total residual variance: Soil test values P	K	pH	Nutrient recommendations P	K	Lime
		g^2 m^{-6}			kg^2 ha^{-2}		$(kg^2\ ha^{-2}) \times 10^4$
Whole-field average	1	573	2030	0.056	1690	1380	23.4
CVM†	2	572	2030	0.054	1680	1380	23.4
Control regions‡	2	529	1780	0.049	1590	1190	24.4
MNY§	3	555	1880	0.056	1640	1240	23.4
Control regions‡	3	521	1650	0.049	1580	1090	19.7
MNY × CVM¶	6	543	1870	0.053	1620	1230	23.2
Control regions‡	6	489	1460	0.047	1490	943	19.7
YRM#	12	407	1520	0.044	1170	938	18.8
Control regions‡	12	414	1300	0.043	1230	814	18.5
98-m grid cell‡	27	291	1030	0.037	871	688	16.9
98-m grid center‡	27	525	1710	0.080	1370	1140	30.1
98-m grid center w/kriging‡	27	314	1390	0.044	1060	889	18.0
Control regions‡	27	317	937	0.036	952	601	16.2
68-m grid cell‡	57	210	640	0.026	624	431	12.2
68-m grid center‡	57	422	1350	0.052	1120	817	18.5
68-m grid center w/kriging‡	57	266	880	0.039	770	569	16.6
Control regions‡	57	218	645	0.026	688	428	13.0

† Yield-based coefficient of variation map (CVM) management zone method.
‡ Indicates that the values reported are the mean of three replications for each grid sample or control region method.
§ Yield-based mean normalized yield (MNY) management zone method.
¶ Yield-based combination of the MNY and CVM management zone methods.
# Yield-based yield region map (YRM) management zone method.

total residual variance for P recommendations ranged from 1060 kg^2 ha^{-2} in Field 1 to 1690 kg^2 ha^{-2} in Field 2. Field 4 had the lowest whole-field total residual variance in soil test K (1450 g^2 m^{-6}) and K recommendations (278 kg^2 ha^{-2}) while Field 1 and Field 2 had the highest total residual variance values in soil test K (5980 g^2 m^{-6}) and K recommendations (1380 kg^2 ha^{-2}), respectively. For soil pH, the whole-field total residual variance ranged from a low in Field 2 of 0.056 to a high in Field 4 of 0.245. Whole-field total residual variance for lime recommendations followed a similar pattern and ranged from 23.4×10^4 kg^2 ha^{-2} in Field 2 to 211×10^4 kg^2 ha^{-2} in Field 4.

However, determining if within-field variability of soil fertility parameters exists is more important than knowing the whole-field total residual variance values. If variability does not exist, then dividing a field into grids, zones, or regions will have little or no effect on fertility management. Whole-field soil fertility and nutrient recommendation summary statistics are shown in Table 6. Soil test P values for all fields ranged from a low of 2.2 g m^{-3} to a high of 129.1 g m^{-3} with whole-field CVs ranging from 42 to 55%. The CVs for P recommendations were also high, ranging from 39 to 68%. Soil test K was highly variable with values ranging from a minimum of 31.3 g m^{-3} to a maximum of 406.6 g m^{-3}. Corresponding CVs ranged from 24 to 50% across all four fields. The CVs for K recommendations were high and ranged from 54 to 145%. Piedmont fields in this region are generally limed to a target pH of 6.0. All four fields

Table 4. The total residual variance calculated from Eq. [2] for soil test P, K, and soil pH as well as P, K, and lime nutrient recommendations for Field 3 by sampling strategy. All values are rounded to three significant figures.

Sampling strategy	Number of zones, grids, or regions	Total residual variance: Soil test values P	K	pH	Nutrient recommendations P	K	Lime
		g^2 m^{-6}			kg^2 ha^{-2}		$(kg^2\ ha^{-2}) \times 10^4$
Whole-field average	1	488	1920	0.079	1300	673	148
CVM†	2	488	1890	0.075	1300	655	139
Control regions‡	2	475	1750	0.058	1290	610	111
MNY§	3	470	1810	0.074	1280	831	150
Control regions‡	3	418	1660	0.049	1110	582	162
MNY × CVM¶	6	450	1760	0.066	1210	652	139
Control regions‡	6	426	1560	0.047	1130	511	71.3
YRM#	10	411	1070	0.045	1120	450	77.5
Control regions‡	10	385	1600	0.049	1030	576	83.9
98-m grid cell‡	38	248	694	0.025	712	285	58.7
98-m grid center‡	38	565	1420	0.052	1400	530	83.5
98-m grid center w/kriging‡	38	337	1180	0.050	1000	529	73.5
Control regions‡	38	162	545	0.012	431	226	37.0

† Yield-based coefficient of variation map (CVM) management zone method.
‡ Indicates that the values reported are the mean of three replications for each grid sample or control region method.
§ Yield-based mean normalized yield (MNY) management zone method.
¶ Yield-based combination of the MNY and CVM management zone methods.
# Yield-based yield region map (YRM) management zone method.

Table 5. The total residual variance calculated from Eq. [2] for soil test P, K, and soil pH as well as P, K, and lime nutrient recommendations for Field 4 by sampling strategy. All values are rounded to three significant figures.

Sampling strategy	Number of zones, grids, or regions	Total residual variance					
		Soil test values			Nutrient recommendations		
		P	K	pH	P	K	Lime
		$g^2\ m^{-6}$			$kg^2\ ha^{-2}$		$(kg^2\ ha^{-2}) \times 10^4$
Whole-field average	1	320	1450	0.245	1250	278	211
CVM†	2	237	1390	0.175	1140	267	161
Control regions‡	2	331	1040	0.243	1340	199	191
MNY§	3	267	1410	0.215	1070	280	207
Control regions‡	3	325	1050	0.218	1310	207	174
MNY × CVM¶	6	226	1340	0.168	917	256	154
Control regions‡	6	235	758	0.133	925	183	105
YRM#	12	159	600	0.058	548	120	48.4
Control regions‡	12	184	512	0.145	741	98.1	111
98-m grid cell‡	29	94.6	339	0.069	418	144	45.9
98-m grid center‡	29	169	564	0.117	686	149	76.9
98-m grid center w/kriging‡	29	175	433	0.081	638	86.4	49.9
Control regions‡	29	101	290	0.062	423	72.8	40.5

† Yield-based coefficient of variation map (CVM) management zone method.
‡ Indicates that the values reported are the mean of three replications for each grid sample or control region method.
§ Yield-based mean normalized yield (MNY) management zone method.
¶ Yield-based combination of the MNY and CVM management zone methods.
# Yield-based yield region map (YRM) management zone method.

had maximum soil test pH values between 6.9 and 7.3. Fields 1, 2, and 3 had minimum soil test pH values that were slightly below target (5.7, 5.9, and 5.6, respectively). Only Field 4 had a minimum soil pH that was considerably below target (5.1). Nonetheless, lime recommendations were highly variable in all fields with CVs ranging from 89 to 273%. Clearly, a high degree of soil fertility variability existed, making it unlikely that a whole-field management approach would effectively describe the soil test and nutrient variability in these fields.

Control Regions

The presence of high within-field variability was also confirmed by the results of randomly dividing the fields into control regions (smaller, equally sized subunits). In all fields, there was a consistent trend of decreasing total residual variance with increasing number of control regions (Tables 2–5 and Fig. 4–7). When Field 1 was divided into 42 control regions (comparable to sampling on a 98-m grid), soil test P, K, and pH total residual variance expressed as a percentage of that found for the whole-field method (Fig. 4) dropped to 65.6, 40.5, and 58.7%, respectively. Total residual variance continued to drop when the field was further divided into 82 control regions. In Field 2, soil test P, K, and pH total residual variances dropped to 55.2, 46.2, and 64.0% (Fig. 5) of the whole-field average when the field was divided into 27 control regions. Even larger reductions in soil test

Table 6. Mean, minimum (min.), maximum (max.), standard deviation (SD), and coefficient of variation (CV) for soil test P, soil test K, and soil pH as well as P, K, and lime nutrient recommendations for each of the four study fields.

Soil fertility parameter		Field 1	Field 2	Field 3	Field 4
Soil test P, $g\ m^{-3}$	Mean	34.3	47.8	47.7	34.4
	Min.	3.5	2.2	13.2	10.8
	Max.	78.1	129.1	112.8	92.4
	SD	14.3	23.4	22.2	18.9
	CV	0.42	0.49	0.47	0.55
Soil test K, $g\ m^{-3}$	Mean	185.7	87.5	125.7	157.5
	Min.	39.1	31.3	67.8	91.9
	Max.	406.6	258.1	269.3	262.0
	SD	77.3	43.8	43.4	37.1
	CV	0.42	0.50	0.35	0.24
Soil pH	Mean	6.5	6.6	6.4	6.2
	Min.	5.7	5.9	5.6	5.1
	Max.	7.1	7.3	6.9	7.0
	SD	0.25	0.24	0.28	0.53
	CV	0.04	0.04	0.04	0.09
P recommendation, $kg\ ha^{-1}$	Mean	83.1	59.4	59.1	84.8
	Min.	1.2	0.0	0.0	0.0
	Max.	162.5	166.5	134.5	141.2
	SD	32.3	40.2	35.8	37.4
	CV	0.39	0.68	0.61	0.44
K recommendation, $kg\ ha^{-1}$	Mean	17.3	65.3	32.4	11.9
	Min.	0.0	0.0	0.0	0.0
	Max.	115.0	125.8	79.1	53.5
	SD	25.1	35.5	24.1	15.0
	CV	1.45	0.54	0.74	1.26
Lime recommendation, $kg\ ha^{-1}$	Mean	413.3	99.3	1189.7	1699.9
	Min.	0.0	0.0	0.0	0.0
	Max.	3078.8	1814.3	3636.8	3778.5
	SD	690.5	271.5	1198.3	1510.1
	CV	1.67	2.73	1.01	0.89

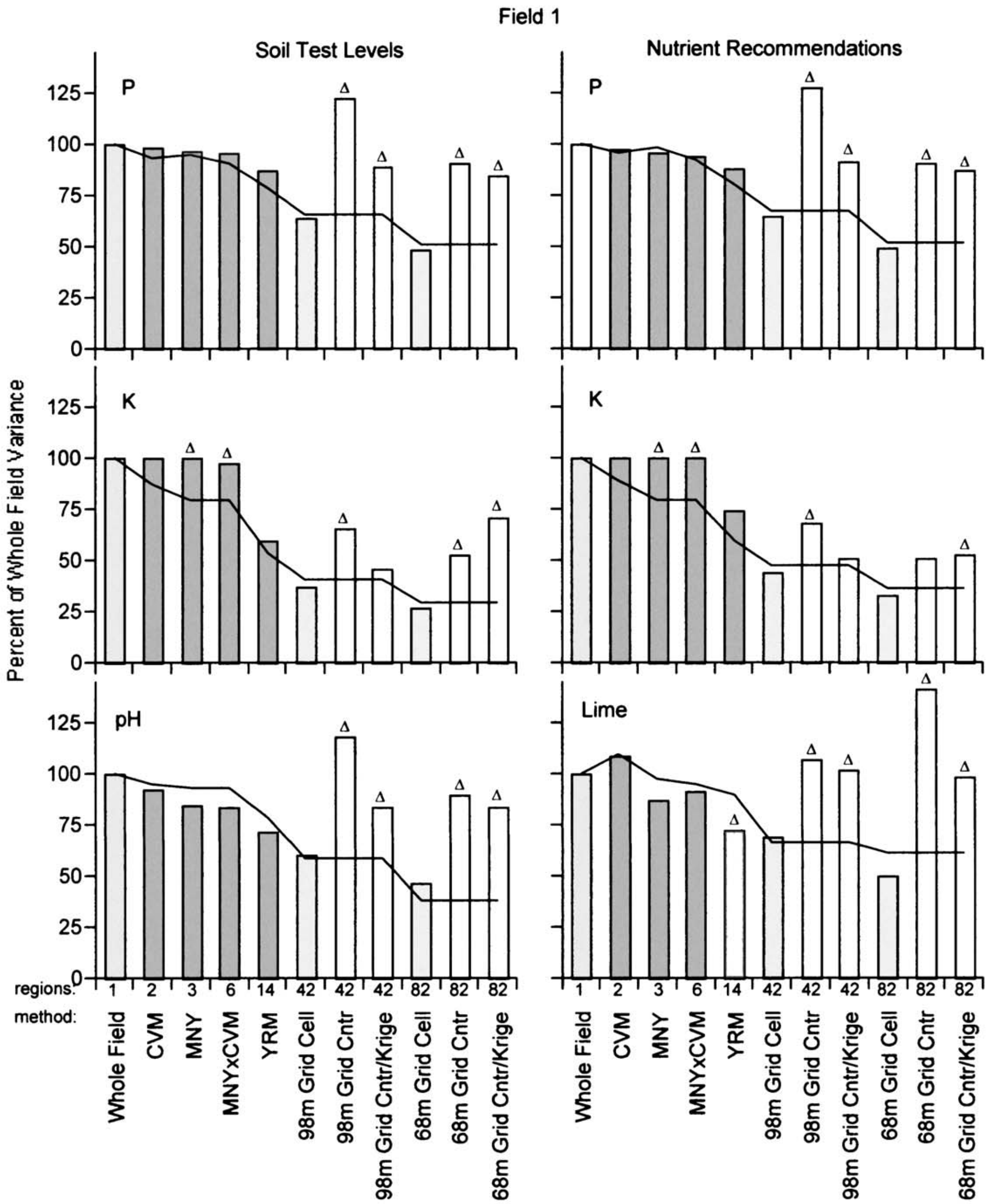

Fig. 4. The residual variance for Field 1, expressed as a percentage of the whole-field variance, of the control regions (solid line), yield-based management zone methods (dark gray bars), the 98- and 68-m grid cell method (hatched bars), and of the 98- and 68-m grid center and grid center with kriging methods (white bars). The number of control regions associated with each method is shown below the horizontal axis. A "Δ" indicates that the residual variance differed from the associated control region by 15 or more percentage points. MNY, mean normalized yield map; CVM, coefficient of variation map; YRM, yield region map.

P, K, and pH total residual variance were evident in Field 3 (Fig. 6) and Field 4 (Fig. 7) when these fields were divided into the number of control regions (38 and 29, respectively) corresponding to sampling on a 98-m grid. As expected, due to the high degree of soil fertility variability, the characterization of within-field soil fertility variability improved as the number of control regions increased.

Yield-Based Management Zones

Yield-based management zones divided the fields into smaller regions of similar yield characteristics. With few exceptions, the CVM, MNY, MNY × CVM, and YRM yield-based management zone techniques equaled or lowered the total residual variance compared with whole-field management (Tables 2–5). Of the yield-based methods, YRM had the greatest reductions in total residual variance compared with whole-field management. In Field 1, YRM explained 12.9, 40.4, and 28.6% more soil test P, K, and pH variability than whole-field management (Table 2). Similarly, YRM explained 12.6, 26.5, and 27.8% more variability in P, K, and lime recommendations than the whole-field method. Fields 2 and 3 showed similar reductions in both soil test P, K, and

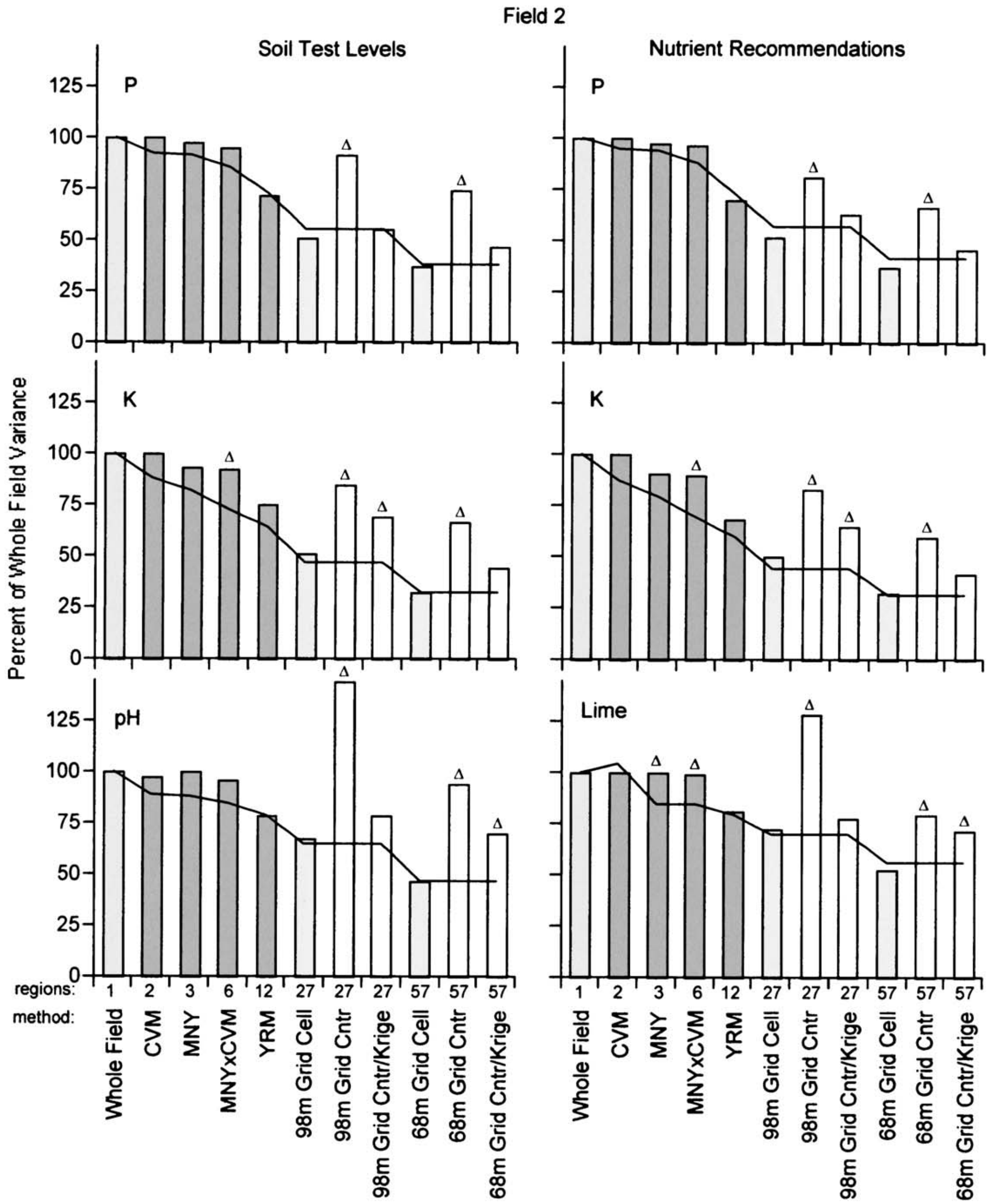

Fig. 5. The residual variance for Field 2, expressed as a percentage of the whole-field variance, of the control regions (solid line), yield-based management zone methods (dark gray bars), the 98- and 68-m grid cell method (hatched bars), and of the 98- and 68-m grid center and grid center with kriging methods (white bars). The number of control regions associated with each method is shown below the horizontal axis. A "Δ" indicates that the residual variance differed from the associated control region by 15 or more percentage points. MNY, mean normalized yield map; CVM, coefficient of variation map; YRM, yield region map.

soil pH as well as P, K, and lime recommendation variability (Tables 3–4). However, YRM was most effective in reducing total residual variance in Field 4 where soil test and nutrient recommendation total residual variances were reduced between 50 and 77% compared with whole-field management (Table 5).

While YRM reduced total residual variance in soil test and nutrient recommendations compared with whole-field management, it is important to determine if the reductions were due to deriving management zones from yield maps or simply due to managing on a smaller scale. By comparing the yield based management zones with their associated control regions (i.e., both the yield-based management zone method and control regions have the same number of management units), we can determine if the reduction in total residual variance is due to the use of yield maps. For soil test P values in Fields 1, 2, and 3, the CVM, MNY, MNY $\times$ CVM, and YRM methods did not capture any more variability in soil test P or P recommendations than the associated control regions (Tables 2–4; Fig. 4–6). In Field 4, the CVM and MNY management zones captured more soil test P variability

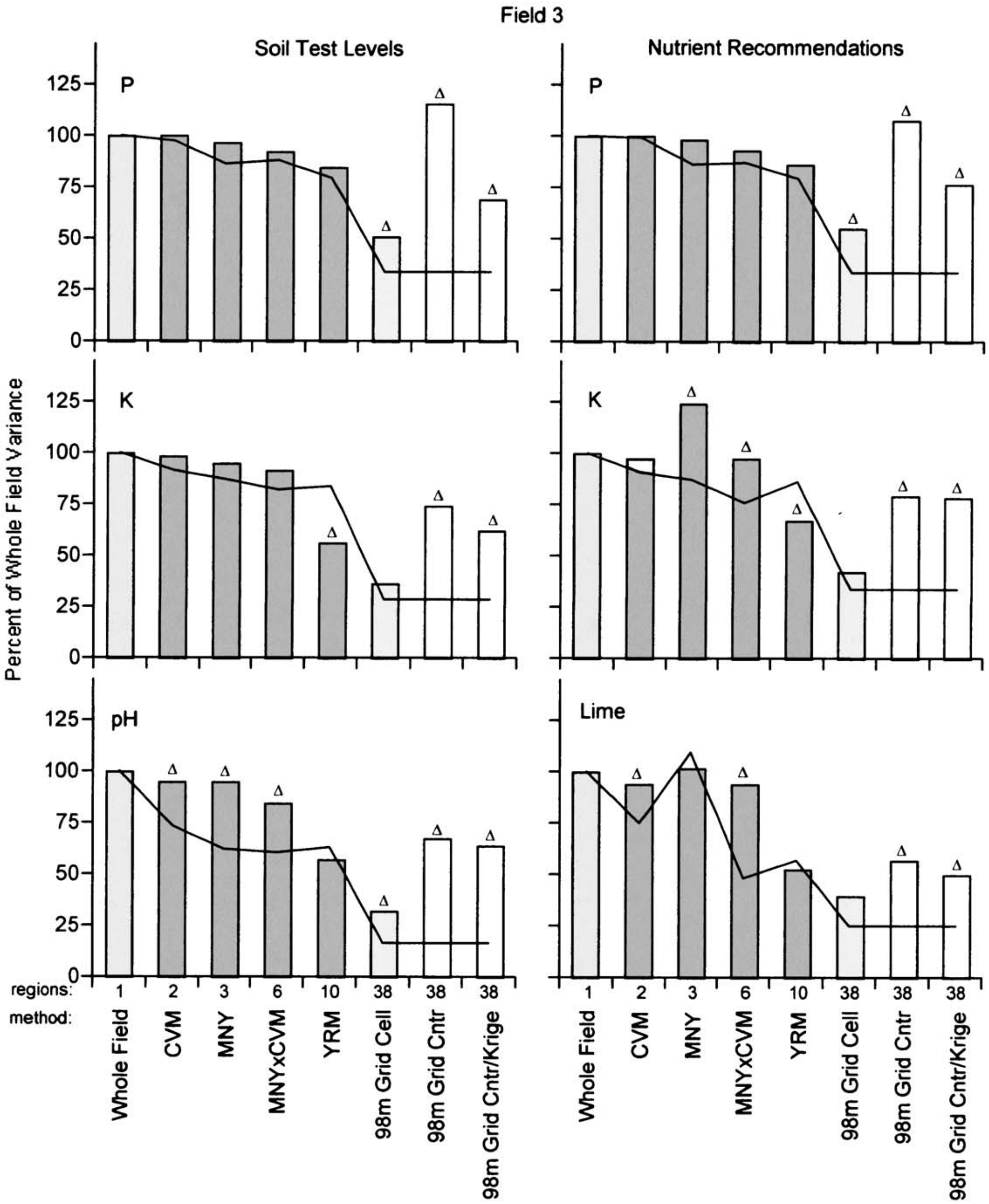

Fig. 6. The residual variance for Field 3, expressed as a percentage of the whole-field variance, of the control regions (solid line), yield-based management zone methods (dark gray bars), the 98- and 68-m grid cell method (hatched bars), and of the 98- and 68-m grid center and grid center with kriging methods (white bars). The number of control regions associated with each method is shown below the horizontal axis. A "Δ" indicates that the residual variance differed from the associated control region by 15 or more percentage points. MNY, mean normalized yield map; CVM, coefficient of variation map; YRM, yield region map.

than the associated control regions (Table 5; Fig. 7), as did the CVM, MNY, and YRM methods for P recommendation. For P recommendations, the YRM method divided the field into 12 management regions and reduced the total residual variance 26% compared with 12 control regions (Table 5; Fig. 7).

For soil test K and K recommendations, the CVM, MNY, and MNY × CVM management zone methods resulted in total residual variances that were similar or higher than those of the associated control regions (Tables 2–5; Fig. 4–7). This indicated that these methods performed no better in creating management zones than a random field division. In fact, in most cases, they were worse. In Field 3, the MNY method even resulted in a higher total residual variance for K recommendations than the whole-field method (Table 4; Fig. 6). In contrast, the YRM method in Fields 1, 2, and 4 resulted in total residual variances that were similar to those of the associated control regions (Tables 2, 3, and 5; Fig. 4, 5, and 7) and in Field 3 captured more variability (lower total residual variance) than the associated control regions (Table 4; Fig. 6). Unlike the CVM, MNY, or MNY ×

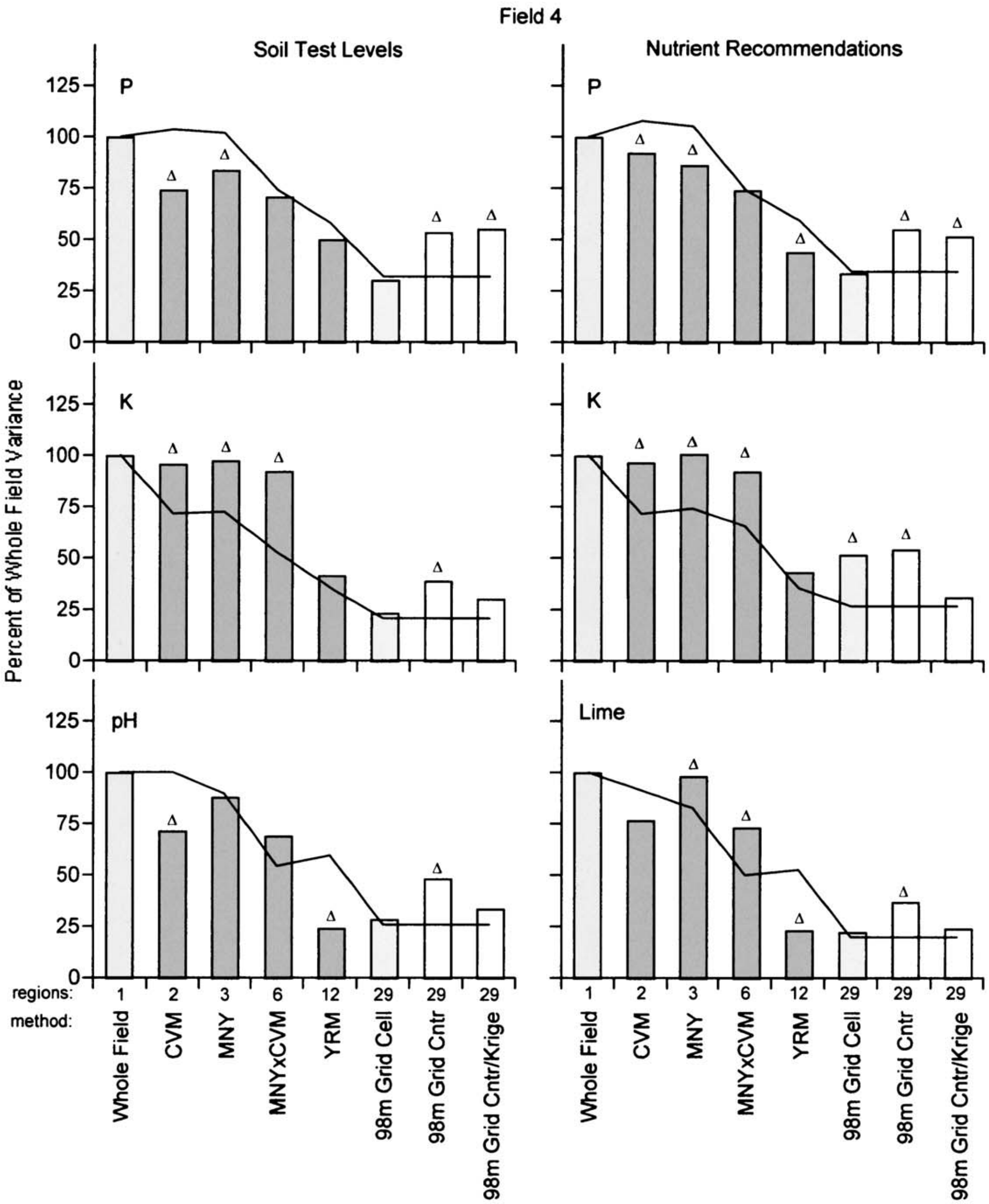

Fig. 7. The residual variance for Field 4, expressed as a percentage of the whole-field variance, of the control regions (solid line), yield-based management zone methods (dark gray bars), the 98- and 68-m grid cell method (hatched bars), and of the 98- and 68-m grid center and grid center with kriging methods (white bars). The number of control regions associated with each method is shown below the horizontal axis. A "Δ" indicates that the residual variance differed from the associated control region by 15 or more percentage points. MNY, mean normalized yield map; CVM, coefficient of variation map; YRM, yield region map.

CVM methods, the YRM method never performed worse than a random division of the fields. In fact, in Field 3, YRM captured 32.7 and 22% more total residual variance in soil test K and K recommendation, respectively, compared with 10 control regions.

In Fields 1, 2, and 3, the CVM, MNY, and MNY × CVM methods also resulted in total residual variance values for both soil pH and lime recommendations that were similar to or higher than those found with the associated control regions (Tables 2–4; Fig. 4–6), indicating that these methods were not better than management zones based on a random division of the field. In these three fields, only the YRM method appeared to be a workable method for developing yield-based management zones. In Field 1, the YRM total residual variance for lime recommendations was 19.4% lower than the associated control regions (Table 2; Fig. 4). The total residual variance for soil test pH in Fields 1, 2, and 3 as well as the lime recommendations in Fields 2 and 3 were not different from the control regions. In Field 4, the CVM method

Table 7. Percentage of land area in each P and K fertility class as defined by the North Carolina Department of Agriculture and Consumer Services (NCDA&CS), and percentage of land area in three soil pH classes for each field.

Soil test value	NCDA&CS response class	Percentage of land area Field 1	Field 2	Field 3	Field 4
		%			
P (g m^{-3})					
P < 30	very high	39.4	24.7	22.2	51.3
30 ≤ P < 60	low to medium	56.8	46.2	54.0	38.5
P ≥ 60	little to none	3.9	29.1	23.8	10.3
K (g m^{-3})					
K < 48.9	very high	1.2	17.6	0.0	0.0
48.9 ≤ K < 97.8	low to medium	12.4	50.5	28.6	5.1
K ≥ 97.8	little to none	86.5	31.9	71.4	94.9
pH					
pH < 6.0	below target	1.9	0.5	6.3	43.6
6.0 ≤ pH < 7.0	at or above target	96.1	92.9	93.7	53.8
pH ≥ 7.0	very high	1.9	6.6	0.0	2.6

resulted in lower or similar total residual variances compared with the control regions for soil pH and lime recommendations, respectively (Fig. 7). The MNY and MNY × CVM methods resulted in similar or worse total residual variances compared with the control regions for soil test pH and lime recommendations, respectively. Conversely, YRM captured considerably more soil test pH and lime recommendation variability than the control regions (60 and 56.3%, respectively) and was as effective as 98-m grid cell sampling (Fig. 7). However, YRM divided the field into only 12 management zones while 98-m grid cell sampling used 29 subdivisions.

By putting these results into context with the three general fertility classes described by the North Carolina Department of Agriculture and Consumer Services (NCDA&CS), we get a better understanding of why the yield-based management zone methods did or did not explain as much soil fertility variability than their associated control regions. The NCDA&CS divides P and K soil test values into three general classes representing soils that are expected to have a crop response to addition of fertilizer (or to changes in soil test values) that is either (i) "very high," (ii) "low to medium," or (iii) "little to none" (Hardy et al., 2003). Table 7 shows the percentage of land area for each field in each of these classes. The percentage of land area below the NCDA&CS-recommended target soil pH of 6.0, between 6.0 and 7.0, and above 7.0 is also shown in Table 7.

In instances where the yield-based management zone methods explained more soil test and nutrient variability than their associated control regions, the NCDA&CS fertility class for the majority of the land area within a field was typically "very high," such as soil test P in Field 4 (Tables 5 and 7). Likewise, the fields that had the majority of land area below a soil pH of 6.0 were fields in which yield-based management zone methods performed better than their associated control regions (Field 4; Tables 5 and 7; Fig. 7). In general, yield-based management zones did not capture more soil test or nutrient variability than their associated control regions in fields where the majority of land area was above a soil pH of 6.0 or in the NCDA&CS fertility classes of "low to medium" or "little to none." This indicates that yield-based management zone methods perform best in fields where soil test values are low (i.e., in the "very high" fertility response class) and in which yield variability is likely to be correlated with soil fertility.

Grid Cell, Grid Center, and Grid Center with Kriging Methods

In Field 1, at both the 98- and 68-m sampling distances, the grid cell method performed better (i.e., it had lower total residual variances for all soil test and nutrient recommendations) than the grid center or the grid center with kriging methods (Table 2; Fig. 4). The 68-m grid cell method accounted for the most variability among all the sampling approaches studied. Total residual variances ranged from 26.7 to 49.5% of those for the whole-field method. Since the grid cell method divided the field into approximately equal areas, the grid cell method and control regions with the same number of areas were about equal in reducing the total residual variance in soil test and nutrient recommendations (Table 2; Fig. 4). In contrast to the grid cell method, both grid center methods did not describe soil test P, soil pH, and P recommendations at the 98-m sampling distance, or lime recommendations even at the 68-m sampling distance, as effectively as the whole-field average approach (Table 2; Fig. 4). This occurred even though the grid center method divided the field into 42 smaller areas. In most cases, kriging resulted in lower total residual variances compared with the grid center method without kriging. The grid center method with kriging at the 98-m sampling distance captured as much or even more variability compared with the 68-m grid center method without kriging. Consequently, while kriging improved the accuracy of the grid center method, the grid cell method was still consistently superior. This differed from the results reported by Wollenhaupt et al. (1994), who found that a grid center method with interpolation (such as kriging) explained more soil P and K variability than a grid cell method.

The results for Field 2 were very similar to those found in Field 1. The largest reduction in total residual variance of soil test and nutrient recommendations was achieved by the grid cell method (Table 3; Fig. 5). Compared with the whole-field average, the 68-m grid cell method resulted in total residual variances between 31.3 and 52.3% (Table 3; Fig. 5). The grid cell method also explained a similar proportion of the soil test and nutrient recommendation variability compared with the same number of control regions. The grid center methods did consistently worse than the grid cell methods. In fact, the 98-m grid center method was not as effective in describing soil pH and lime recommendation variability as the whole-field average approach. As in Field 1, kriging improved the grid center method, and total residual variances of the 98-m grid center with kriging method were often as good as or better than those found for the 68-m grid center method without kriging.

In Field 3, the grid cell method again captured more variability than any other method (Table 4; Fig. 6). Grid cell (98 m) total residual variances ranged from 32.0 to 54.8% of the whole-field variance. Interestingly, for soil test P, pH, and P recommendations, the grid cell total residual variance was slightly higher than that associated with the control regions. This is most likely due to the smaller number of soil sample points used in the analysis and/or the use of a rectangular soil sample grid instead of the equilateral triangular soil sample grid used in Fields 1 and 2. By using a rectangular grid, the number of soil samples in each 98-m grid was reduced compared with the equilateral triangular grid. Nonetheless, the grid cell method was quite successful in capturing soil variability. In contrast, the grid center method, even with kriging, resulted in consistently higher total residual variances. For example, the grid center method for soil test P and P recommendations resulted in residual variances that were higher than the whole-field average approach (115.7 and 107.3%, respectively, see Fig. 6). Additionally, the impact of kriging was not always evident. For soil test P and P recommendations, kriging resulted in lower total residual variances compared with the grid center method alone; however, for all other parameters, kriging resulted in little to no improvement.

In Field 4, all the grid sampling methods reduced total residual variances in soil test and nutrient variability compared with the whole-field average (Table 5; Fig. 7). Similar to Fields 1, 2, and 3, the grid cell method generally had lower total residual variance for soil test and nutrient recommendations. Compared with the whole-field average, the 98-m grid cell method resulted in soil test and nutrient recommendation variances as low as 21.8% (Table 5; Fig. 7). As in Field 3, the grid cell total residual variance was sometimes higher than that found for the associated control regions (e.g., K nutrient recommendations), probably due to the use of a rectangular sampling grid in these fields. Unlike in the other fields, the grid cell method did not always capture the most within-field variance. For soil test pH and lime recommendations, the YRM method was either similar or superior (Table 5; Fig. 7) even though YRM only divided the field into 12 management regions compared with 29 used by the 98-m grid sampling methods.

CONCLUSIONS

Our main objective was to determine if multiyear yield data could be used to delineate management zones that would accurately describe spatial variability in soil test and nutrient recommendation values. We also wanted to compare the efficiency of various yield-based management zone methods with traditional grid cell and grid center sampling approaches. Significant variability in both soil test and nutrient recommendations existed in all four study fields to test our objective.

The only yield-based method that showed promise for capturing soil fertility variability was the YRM method. In many instances, YRM was more efficient at capturing soil fertility variability than the control regions, the 98-m grid center method, and the 98-m grid center with kriging methods. The YRM method appeared to be most efficient when a large percentage of the land area in a field had soil test values that were in the NCDA&CS "very high" fertility response class. Where this occurred, the YRM method captured about the same amount of within-field variability in nutrient recommendations as did the 98-m grid cell method. The YRM method, however, was more efficient in capturing this soil fertility variability due to its reduced number of sampling regions.

However, our data make it clear that in these fields, 68-m grid cell sampling was the most effective way to capture within-field nutrient variability. This contrasts with the finding of Wollenhaupt et al. (1994), in that grid cell sampling consistently captured more soil fertility variability then did the grid center method. While kriging increased the efficiency of grid center sampling, it never matched the ability of the grid cell method to capture within-field variability. Clearly, in these fields, sampling at more than one location inside a grid was important.

These results have important implications for soil sampling. Current grid sampling practices generally use a grid center technique. Our results indicate that the grid center methods were not very effective in capturing soil test and nutrient variability. In fact, in most cases, our YRM method performed as well as or better than the grid center methods we evaluated while reducing the number of sampling regions. Therefore, as our results indicate, we would not recommend a grid center method for soil sampling. Instead we would recommend a grid cell sampling strategy. Our results indicate that grid cell sampling is the most effective sampling technique at capturing soil test and nutrient variability. However, our research was on a limited data set, and further research is required to confirm our results in multiple environments.

Our results were also very promising for the YRM yield-based system for developing management zones. In many instance, YRM was nearly as effective in capturing nutrient recommendation variability as the 98-m grid cell method. These results show that soil fertility management zones derived from multiyear yield data can effectively capture soil test and nutrient variability. Collecting multiple samples within a YRM zone and compositing them (grid cell type sampling) to obtain a single analytical result for a zone would likely be a cost- and time-effective way to characterize soil spatial variability for variable-rate P, K, and lime management. Further research is needed to determine whether our approach for developing yield-based management zones captures soil test and nutrient variability in other environments, and whether site-specific nutrient and lime applications based on such zones are agronomically efficient.

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